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Feature Article

Farmers' Incentives and the Adoption of Sustainable Plant Protection Approaches

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Abstract

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Adopting sustainable plant protection approaches (SPPAs) is critical for addressing environmental challenges and ensuring sustainable agricultural systems. This review synthesizes current knowledge on the factors influencing farmers' adoption of SPPAs, focusing on behavioral, social, and institutional drivers. Farm-related determinants include health concerns, risk perceptions, economic stability, and literacy regarding SPPA benefits and implementation. Non-farm factors such as social norms, government policies, and stakeholder interactions also shape adoption behaviors. The role of social networks and extension services is underscored as critical mechanisms for knowledge transfer and motivation, with farmer-to-farmer interactions emerging as particularly influential. Despite evidence supporting the environmental and economic benefits of SPPAs, barriers such as high costs, perceived inefficacy, and limited access to information and technical resources persist. Government interventions, including subsidies, training programs, and crop insurance, are identified as key tools to mitigate risks and financial burdens associated with SPPAs. However, systemic issues, such as fragmented policies and conflicting market pressures, often hinder the adoption of SPPAs. This review highlights the need for integrated, evidence-based strategies that align incentives across stakeholders, leverage psychological insights into behavior change, and address regional and cultural differences in agricultural systems. Advancing SPPA adoption requires long-term research and coordinated efforts among researchers, policymakers, and the agricultural community to build resilient and sustainable farming practices globally.

Key words: Farmers' behavior, Integrated pest management (IPM), Agricultural sustainability, Agricultural policy, Stakeholders.

INTRODUCTION

As the human population continues to rise, our environment is facing unprecedented threats (IPCC 2021). Particularly, in an agricultural context, the demand for food is rising (Tilman *et al.* 2011). However, climate change has increased the frequency and severity of many abiotic stresses which have increased the challenges in maintaining food production in many regions (IPCC 2021). Influenced by the fluctuation in abiotic conditions, biotic challenges increase, including emerging and spreading pests and pathogens that lead to severe yield loss worldwide (Savary *et al.* 2019; IPPC 2021; Schneider *et al.* 2022). To combat these biotic challenges, synthetic pesti-

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cides have been used as one of the key methods that effectively inhibit the spread and growth of pests and pathogens since the Green Revolution have now become the single most commonly used approach of plant protection against biotic stresses (Matthews 2018). However, it is also well established that the unsustainable and excessive use of pesticides can be damaging to the environment and human societies (Lundgren & Fausti 2015; Sánchez-Bayo 2021), and it is now widely recognized in academia, most governments, and societies that transitioning away from the heavy reliance of unsustainable use of synthetic pesticide is a key way to a sustainable food production system (Horrigan *et al.* 2002; Wezel *et al.* 2014; Barzman *et al.* 2015; Finger *et al.* 2024).

Sustainable plant protection approaches (SPPAs) are defined as plant protection tools or behaviors that aim to control pests and pathogens in a way that is both environmentally sustainable and economically viable over the long term, prioritizing income stability and resilience rather than short-term profit maximization (Finger *et al.* 2024). This definition does not exclude the use of synthetic pesticides as a plant protection approach. When the application of pesticide is scientifically evaluated to be more environmentally friendly and sustainable, it can also be considered as a behavioral SPPAs (Lykogianni *et al.* 2021; Finger *et al.* 2024). Other tools of plant protection are believed to be innately more sustainable including, the use of biological control agents (Baker *et al.* 2020; Tomar *et al.* 2024), natural products (Thuerig & Tamm 2020), ecological farming practices (e.g., intercropping, crop rotation, trap crop, cover crop, agroforestry) (Deguine *et al.* 2023). While these sustainable approaches have been proven in some cases to lead to good pest control outcomes (Deguine *et al.* 2023), they are far from frequently adopted by farmers around the world (Finger *et al.* 2024).

Agriculture has changed throughout history, and in modern years, the main scheme of agriculture has been heavily influenced by the Green Revolution, which leads to agricultural industrialization. Agricultural industrialization is the process of using advanced technology, machinery, and scientific techniques to increase agricultural productivity and efficiency (Evenson & Gollin 2003). This involves the adoption of high-yield crop varieties, synthetic fertilizers, pesticides, and irrigation systems, as well as the integration of farming with large-scale production, processing, and distribution systems. This shift has transformed agriculture into a more mechanized and intensive industry, focused on maximizing output and improving cost-efficiency to meet the increasing demands of global food markets (Evenson & Gollin 2003). Although the industrialization of agriculture and productivism perspective has improved productivity across many regions globally, the prioritization of profit and productivity, along with the neglect of other agricultural values (such as ecosystem services), has led to numerous unsustainable issues in recent years (Deguine *et al.* 2021). This has also led to rigidity in production practices, particularly in pest control methods, where reliance on established practices makes farmers less likely to adopt alternative approaches, creating significant barriers to transforming agricultural production systems (Béné *et al.* 2019; Finger *et al.* 2024).

From the perspective of pest control, synthetic pesticides provide an effective and predictable means of eliminating pests in the short term, a level of efficacy unmatched by more sustainable approaches (Deguine *et al.* 2021). These sustainable methods, while less effective in the short term, protect crops over time, sustain soil and land fertility, and offer additional benefits such as maintaining ecosystem functions and addressing the environmental challenges posed by synthetic pesticides (Deguine *et al.* 2023). To enhance the adoption of SPPAs and promote a sustainable agricultural system, there is a constant effort to develop SPPAs that are as effective as synthetic pesticides and meet the productivity standards of modern agricultural production systems (Finger *et al.* 2024). However, despite the availability of effective SPPAs, farmers do not always adopt these measures. Recognizing this issue, it is important to understand the willingness and incentives of farmers in choosing plant protection practices. Identifying factors that change farmer behavior into adopting SPPAs could be key to establishing a more sustainable plant protection scheme.

With that said, there is a significant lack of comprehensive reviews on this specific topic (see Finger *et al.* 2024). To address this knowledge gap, this review aims to bridge the divide between identifying the causes of low adoption rates and proposing solutions to increase the use of SPPAs. The review will be divided into three sections: first, summarizing and synthesizing key farm-related and non-farm factors influencing farmers' incentives to adopt SPPAs on a global scale; second, examining the role of various stakeholders in shaping adoption decisions; and finally, discussing the key challenges and potential solutions for enhancing the adoption of SPPAs.

FACTORS DETERMINING THE SPPAS ADOPTION BY FARMERS

The adoption of SPPAs is a behavioral process influenced by a complex interplay of factors (Fig. 1), similar to other human behaviors, making it challenging to disentangle these determinants

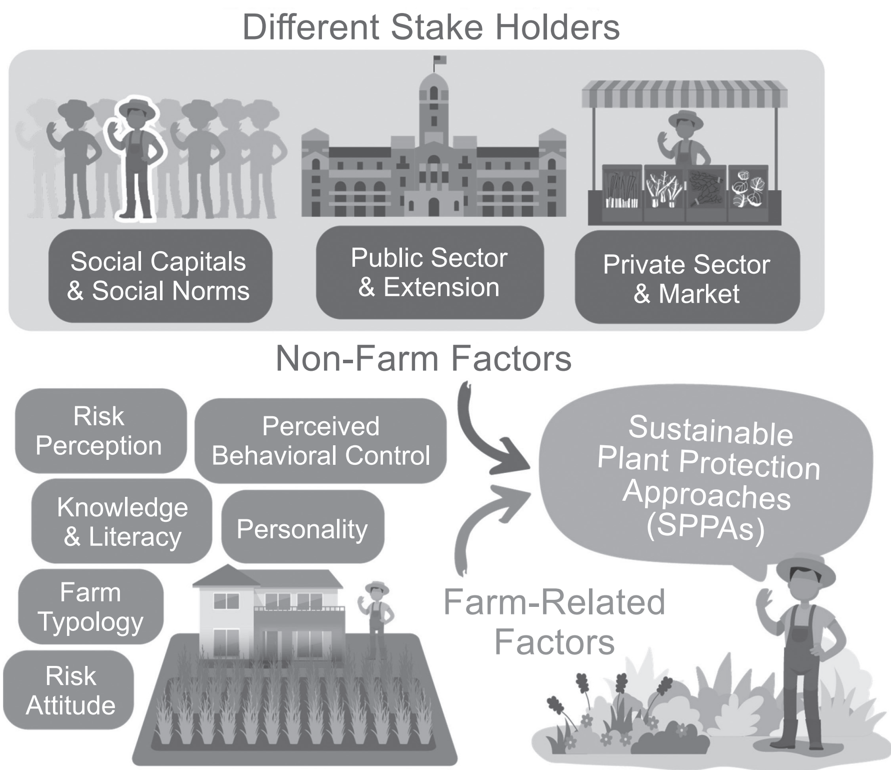

Fig. 1. Drivers of farmers' behavior and the adoption of sustainable plant protection approaches (SPPAs). This conceptual framework illustrates the interplay between farm-related and non-farm factors influencing farmers' adoption of SPPA practices. Farm-related factors include farm type, risk attitude, risk perception, knowledge, and literacy, which shape farmers' ability and willingness to implement SPPAs. Non-farm factors, such as social capital and norms, public sector policies and extension services, and market-driven incentives from the private sector, further interact to drive behavioral changes. Personality traits and perceived behavioral control act as cross-cutting influences between these domains. The figure highlights how these interconnected drivers collectively affect the adoption of SPPAs, emphasizing the complexity and multidimensional nature of farmers' decision-making processes.

(Albarracín *et al.* 2024). Recent studies, however, have identified key factors shaping farmers' decisions and behaviors regarding the use of SPPAs. These factors can broadly be categorized into two groups: farm-related factors and non-farm factors. Farm-related factors include personality (Knapp *et al.* 2021), relationships with nature (Yoshida *et al.* 2018), trust in information sources (Jin *et al.* 2015), risk tolerance (Begho 2021), risk perception (Toma & Mathijs 2007), knowledge (Shahidullah *et al.* 2023), beliefs (Ataei *et al.* 2021), perceived behavioral control (Dessart *et al.* 2019), and farm characteristics (Meunier *et al.* 2024). Non-farm factors include social norms (Villamayor-Tomas *et al.* 2019), social identity (Sulemana & James 2014), social capitals (de Krom 2017), communication mechanisms (Breetz *et al.* 2005), and other stakeholders in the socio-ecosystem (Brinks & de Kool 2006; Dessart *et al.* 2019; Meunier *et al.* 2024). The interactions among these factors are complex and challenging to fully comprehend, particularly in how they collectively influence farmers' behavior (Ren *et al.* 2022; Li *et al.* 2024). However, individual studies focusing on specific aspects of farmers' behavior have provided critical insights into the relationships between these factors. These findings will be examined in detail in the following sections.

Farm-related factors

Traditional plant protection practices typically involve the use of synthetic pesticides, which are associated with well-documented health risks (Damalas & Eleftherohorinos 2011). Consequently, health and well-being concerns are key factors influencing the adoption of SPPAs, which pose lower health risks. Vegetable farmers in Bangladesh perform unsafe pesticide practices due to a lack of awareness of the links between pesticide use and non-communicable diseases (Shahidullah *et al.* 2023). Health motivation was also among the key factors in promoting green pesticide use by Iranian farmers (Ataei *et al.* 2021).

Besides health-related risks, there are many other risks associated with crop production (Duong *et al.* 2019). The perception of these risks of individual farmers influences their adoption of SPPAs. For example, farmers' perception of environmental risks is a key factor in the adoption of SPPAs in Switzerland. Those who view pesticide use as significantly harmful to the environment and human health are more likely to adopt pesticide-free practices. Notably, concerns about environmental impacts- such as the long-term effects on soil health and biodiversity- often outweigh health-related considerations in influencing their decision-making (Finger & Möhring 2022). Risk perception is defined as a farmer's evaluation of the likelihood that specific risks will impact their business, as well as the potential consequences of those risks (Gardebroek 2006). These risks are perceived differently across regions, with low- and middle-income countries often concerned more about weather-related risks, while biosecurity (pest and disease outbreak, invasive species, etc.) was more frequently noted in developed nations (Duong *et al.* 2019). However, it is important to recognize that weather-related and pest-related risks are inherently interconnected (Mattson & Haack 1987; Peng *et al.* 2020). Weather events, such as extreme storms, droughts, or floods, not only pose immediate threats to crop yields but also increase the likelihood and severity of pest and disease outbreaks (Mattson & Haack 1987; Risch 1987). Furthermore, such events may create conditions conducive to the establishment and spread of invasive species, highlighting the inextricable link between climatic and biosecurity risks for farmers in all regions (Diez *et al.* 2012).

Farmers' socioeconomic backgrounds, including education, farm size, and experience, influence their risk perception, affecting their adoption of various risk management strategies, including SPPAs (Duong *et al.* 2019; Nastis *et al.* 2019). Particularly important is the role of economic factors, such as land ownership and investment behavior, in influencing environmental risk perception and the adoption of SPPAs, such as organic farming programs (Toma & Mathijs 2007). Similar findings were reported in many studies which found that farmer's interest in participating in SPPAs due to environmental risk is often influenced by their economic factors (Wilson & Hart 2000). Economic factors, such as farm size and income, also influence the ability to process and utilize information, which is usually positively correlated with the perceived environmental risks of using pesticides (Tucker & Napier 2001). While education can enhance cognitive capacity and exposure to risk-related information, it is not directly influenced by economic factors as implied in this study.

Risk attitude refers to a farmer's perspective on risk and its implications, encompassing a spectrum from caution (risk-averse) to indifference (risk-neutral) to a propensity for risk-taking (Gardebroek 2006). A critical element of this is risk tolerance, which significantly influences a farmer's willingness to adopt sustainable practices. Generally, risk-averse farmers, who often face income volatility, high debt, and low profit margins, may perceive financial risks in adopting innovative, sustainable methods. These risks stem not only from the potential upfront costs of SPPAs but also from concerns about their lower efficiency compared to synthetic pesticides under conditions where pesticide resistance is not yet a significant issue. For example, Mkenda *et al.* (2015) demonstrated that synthetic pesticides like Karate are highly effective at controlling pests, often outperforming plant-based alternatives in immediate pest reduction. Similarly, Klonsky (2012) found synthetic pesticides more effective and less labor-intensive than organic methods, especially for labor-intensive crops like strawberries. While SPPAs can support pest control and ecosystem services, their perceived costs and labor demands may deter adoption without stronger incentives or evidence of long-term benefits. In contrast, risk-tolerant farmers, who are more accepting of uncertainties, tend to adopt innovations such as organic farming more readily (Dessart *et al.* 2019). Research focusing on small-scale farmers indicates that risk tolerance is shaped by various factors, including experience, education, farming income, access to capital, land ownership, and land size (Agussabti *et al.* 2020).

One of the most important factors influencing the adoption of SPPAs is how well farmers understand the risks and benefits of particular SPPAs, namely literacy regarding SPPAs. For instance, pesticide application knowledge, including the associated behavioral skills, can promote SPPAs (Li *et al.* 2023). Farmers with higher education were more likely to recognize both the pros and cons of pesticides and showed greater support for adopting biological control methods in Iranian (Abdollahzadeh *et al.* 2015). Higher literacy leads to safer pesticide use in Nepal, with men being more informed than women (Atreya 2007). In Bangladesh, educated watermelon farmers are more likely to adopt SPPAs. Education increases awareness of agrochemical risks and the benefits of sustainable practices, making it a key factor in promoting the transition to organic methods (Hoque *et al.* 2022). Similarly, the educational level significantly influences farmers' pesticide use against mosquitoes in rural farmers in Côte d'Ivoire (Kouame *et al.* 2022). Low levels of education and lack of proper training can lead to unsustainable use of pesticides in some regions due to the focus on maximizing profits. Many farmers are unaware of pesticide risks or fail to adopt protective measures, prioritizing higher yields over safety and environmental concerns (Akter *et al.* 2018).

The adoption of SPPAs by farmers is significantly influenced by their perceived behavioral control. This concept encompasses their confidence in their ability to successfully implement these approaches and their belief in their capacity to overcome potential barriers. Higher perceived behavioral control is associated with stronger intentions to engage in such practices, as it reflects both their self-efficacy and the availability of external resources and support necessary for execution (Albarracín *et al.* 2024). In Vietnam, farmers who feel confident in their ability to implement SPPA practices are more likely to adopt them, while social pressures or expectations (i.e., subjective norms) have little impact on their decisions. Younger farmers are more inclined to adopt SPPAs than older farmers, who often lack confidence in their ability to make the transition. This highlights the importance of improving farmers' perceived control through targeted policies and educational programs to promote the wider adoption of sustainable practices (Phung & Dao 2024). A similar phenomenon was observed among Swiss fruit farmers, where the belief in their ability to influence future outcomes played a critical role in their adoption of preventive pest management measures (Knapp *et al.* 2021).

The personality of the farmer is known to influence farmers' behavior. Personality traits refer to distinctive patterns in how individuals think, feel, and behave (Bergner 2020). Traits such as extraversion, openness to new experiences, agreeableness, neuroticism, and conscientiousness can significantly influence a farmer's decision-making (Costa & McCrae 1992; Austin *et al.* 2001; Crase & Maybery 2004). Traits such as openness and agreeableness are crucial in determining how farmers adopt best practices for managing remnant bush and revegetation in Australia (Crase & Maybery 2004).

Trust is a multidimensional construct encompassing personal trust (farmers' belief in the individual advisor), relational trust (farmers' perception that the advisor understands and respects their goals), and institutional trust (farmers' confidence in the formal source of the message, such as public, private, or charitable institutions) (Sutherland *et al.* 2013). Several studies have demonstrated the impact of institutional trust- confidence in the fairness and reliability of organizations- on achieving behavioral change and adoption of SPPAs through advisory services (Sutherland *et al.* 2013; Barghusen *et al.* 2021; Pierrette Coulibaly *et al.* 2021; Albarracín *et al.* 2024; Meunier *et al.* 2024). It was found that in some cases, the longevity and expertise of a service provider are more important for building relational trust than whether the advisory service is public, private, or charitable (Sutherland *et al.* 2013). Farmers in two contrasting European countries (Hungary and the UK) were found to place trust in sources whom they perceived as empathetic towards their needs (Rust *et al.* 2022). Another case in China (Hebei cotton) concluded the use of SPPAs is influenced jointly by information provision and trust (Jin *et al.* 2015).

Farmer typologies, which classify farmers based on shared characteristics such as resource endowments, priorities, and production strategies, can significantly influence the adoption of SPPAs (Van der Ploeg *et al.* 2009). The adoption of SPPAs by farmers from Hainan, China, is significantly associated with their capital endowments (Xu *et al.* 2023), which refers to the capability and resources a farmer household has to support production and livelihood. Indicators of capital endowments include natural capital (e.g., farmland area), economic capital (e.g., household income), human capital (e.g., number of labor force, health status), and social capital (e.g., interpersonal interaction, communication, and institutional trust) (Xu *et al.* 2023). Farmers that prioritized yields were less likely to support SPPAs, as they perceived more benefits from pesticide use in boosting productivity in Iran (Abdollahzadeh *et al.* 2015). Larger, wealthier farms with more access to resources are often more capable of adopting sustainable practices due to their ability to absorb risks and manage the upfront costs of implementation. In contrast, small-scale farms may struggle to adopt such practices due to limited capital and higher perceived risks (Ren *et al.* 2019). Off-farm income, often viewed as a risk management strategy against whole-farm risk, plays a crucial role in facilitating the adoption of SPPAs, as farmers with such income sources tend to be more willing to take on the perceived risks associated with implementing these practices (Sharifzadeh *et al.* 2018). Moreover, using one risk management strategy can trigger the adoption of another, highlighting the interactive nature of risk management approaches. Additionally, farms that produce high-value or export-oriented crops are more likely to adopt sustainable methods driven by market incentives and regulatory pressures (Peeters *et al.* 2015).

Although not directly related to plant protection practices, some cases illustrate that farmers' relationships with nature play a crucial role in shaping their sustainable agricultural practices. For example, farmers in the US Midwest, particularly in two Illinois watersheds, are instrumental in managing nitrogen fertilizers and addressing water quality issues (Yoshida *et al.* 2018). Surveys and interviews revealed a spectrum of perspectives: while some farmers adopt a "Master" view, attributing environmental problems to human activity, many embrace a stewardship or partnership ethos with nature, which drives their conservation efforts. However, despite these ecological values, production pressures, livelihood concerns, and systemic challenges often constrain their ability to fully implement conservation practices (Yoshida *et al.* 2018). This finding highlights the multifaceted human–nature relationships underlying agricultural decisions, with critical implications for resource management, conservation efforts, and environmental sustainability.

Non-farm factors

Studies looking at farmer's use of SPPAs have identified that non-farm drivers as a common driver toward SPPAs (Rogers *et al.* 2023). Starting from the more local factors, farmers' behavior associated with SPPAs is often influenced by social capital (Bhandari & Yasunobu 2009). Social capital refers to the networks, relationships, and norms that facilitate collective action within a society. Broadly, it is understood as a collective resource composed of shared values, beliefs, trust, social relationships, and institutions that enable cooperation and collective action for mutual benefit (Bhandari & Yasunobu 2009). Factors associated with social capital include the status of the farm, the frequency with which farmers share information with others, whether farmers are involved in agricultural associations, and whether they are influenced by the business behaviors of others. While not directly linked to SPPAs, behaviors related to sustainable fertilizer use, such as fertilizer reduction, have been found to correlate strongly with social capital (Zheng *et al.* 2022). The impact of social capital, such as communication among farmers, is highest for part-time farmers, followed by large-scale professional full-time farmers, and lowest for small-scale full-time farmers (Zheng *et al.* 2022). This suggests that social capital may also interact closely with farm status to influence the adoption of SPPAs.

The interactions among farms and other stakeholders contribute to the development of specific social norms. A social norm refers to unwritten rules that guide behavior in society based on what is commonly done or believed to be appropriate (Albarracín *et al.* 2024). An injunctive norm specifically refers to the perception of what behaviors are approved or disapproved of by others, focusing on moral expectations. It reflects the social pressure to conform to behaviors that are seen as "right" or "wrong," such as feeling the need to recycle because it is widely viewed as the correct action in a community. These norms play an important role in facilitating the adoption of SPPAs. For example, peer influence and the behavior of neighboring farmers significantly impacted smallholder farmers' decisions in Cambodia to adopt sustainable pest control methods, such as setting aside land to support natural enemies (Bell *et al.* 2016). A similar pattern was observed among Iranian farmers, where social norms positively influenced their intention to use green pesticides (Ataei *et al.* 2021). In developed countries, evidence suggests similar dynamics. For instance, European farmers' participation in agri-environmental schemes was shaped by peer orientation and social norms, even within robust institutional frameworks (Bartkowski & Bartke 2018). However, while these factors are important, their influence remains understudied, particularly in developed settings, highlighting a need for further research to optimize governance strategies leveraging social dynamics.

One key factor that facilitates the adoption of SPPAs is governmental subsidies or financial support. In Cambodia, financial incentives for maintaining non-crop habitats encouraged farmers to collaborate and adopt SPPAs, helping to overcome coordination challenges and mitigate the risk of free riders (Bell *et al.* 2016). While this study does not directly demonstrate an increase in SPPA adoption, research shows that government fiscal expenditure on agriculture is positively associated with sustainable agricultural economic development (Zhang & Zhang 2024). This suggests that government support enhances the overall value of sustainable agriculture, which likely reflects improved implementation of SPPAs (Zhang & Zhang 2024). Subsidies can be effective, but their impact likely varies depending on program design and local conditions, highlighting the need for further evaluation.

Markets play a significant role in increasing the adoption of sustainable agricultural practices (Stavins 1989; Grabosky 1994), particularly in plant protection. Market forces, such as consumer preferences, regulatory requirements, and financial incentives, drive businesses to adopt environmentally friendly practices. In plant protection, these forces encourage the implementation of integrated pest management (IPM) and reduced pesticide use as markets and consumers increasingly favor products with lower environmental impacts. Financial institutions and private-sector collaborations reinforce these efforts by rewarding compliance with environmental standards. The rise of environmental, social, and governance (ESG) criteria has further incentivized farmers to adopt SPPAs, as financial benefits and market access increasingly depend on meeting these standards. Investor and stakeholder pressure has made ESG integration a necessity for managing risks and enhancing competitiveness. This trend aligns environmental sustainability with economic incentives, fostering broader adoption of sustainable practices (Zaccone & Pedrini 2020). Additionally, growing consumer demand for sustainability pressures agricultural producers to innovate and adopt green technologies, including safer and more sustainable plant protection methods (Grabosky 1994; Codron *et al.* 2014; Martins *et al.* 2025). The relationship between farmers and buyers plays a significant role in the adoption of SPPAs. Farmers with formal contracts with lead companies- often including provisions such as quality standards and technical support- are much more likely to adopt SPPAs, as seen in Chile's vegetable sector. In contrast, farmers relying on informal agreements, particularly with intermediaries, are less likely to implement these sustainable practices. This research highlights the critical role formal contracts play in encouraging the adoption of environmentally friendly farming methods (Benitez-Altuna *et al.* 2023). Market influence on the adoption of SPPAs is particularly obvious in export-driven sectors. In the case of fresh tomato production in Morocco and Turkey, private market regulations and the safety demands of importing countries are the primary drivers of practices like IPM and good agricultural practices (GAP). Moroccan growers, exposed to stringent European Union safety standards, show higher adoption rates of IPM and GAP due to strong vertical integration in supply chains and collective compliance efforts. Conversely, Turkish growers have lower adoption rates, largely influenced by weaker safety requirements in traditional export markets and less developed private regulatory systems (Codron *et al.* 2014).

The adoption of SPPAs by farmers is significantly influenced by market demand and consumer trust in green products. Wang *et al.* (2024) demonstrate that increased consumer preference for high-quality, environmentally friendly products raises market prices and trust, creating economic incentives for farmers. These market-driven incentives are amplified by the government's regulatory efforts and ecological subsidies. While subsidies and stable market prices for green products help offset production costs and risks, they complement rather than substitute market demand. As the study illustrates, market demand alone may not always outweigh other barriers, such as farmers' skepticism or high production costs. Instead, a dynamic interplay between consumer demand, government support, and market regulations fosters a stable equilibrium, promoting the adoption of SPPAs (Wang *et al.* 2024). The agricultural product market is not the only market influencing the adoption of SPPAs; other markets, such as the land market, can also have an indirect impact (Shen & Wang 2024). A study in China found that market-oriented land allocation- driven by rural-to-urban migration and resulting in larger farm sizes- promoted cropland quality protection activities, including greater adoption of SPPAs. This is believed to be linked to increased farm size and higher agricultural income (Shen & Wang 2024).

STAKEHOLDERS AND FARMERS' ADOPTION OF SPPAS

Farmers' engagement in SPPAs is significantly impacted by their interactions with various stakeholders, including farmers, public, and private sectors (Scherfranz *et al.* 2024). While we recognize that these stakeholders could also be categorized as non-farm factors, in this section, we aim to focus more on the interactions between these actors. This section provides a different perspective discussing how different factors influence the adoption of SPPAs. As mentioned before, the market exerts a strong influence on the adoption of SPPAs, and buyers can, therefore, influence the adoption of SPPAs. In the Chile example, farmers involved in informal contracts were less likely to adopt SPPAs (Benitez-Altuna *et al.* 2023). Nestle's production standards in Yunnan can facilitate the use of SPPAs (Rogers *et al.* 2023). Agribusiness can, therefore, have a positive impact on the adoption of SPPAs. On the other hand, industry influence can also be a barrier to the adoption of SPPAs. A study on cashew farms in Ghana found a different trend: farmers with a strong inclination towards contract farming showed lower probabilities of using sustainable agricultural practices, possibly due to the inputs of fertilizers and pesticides provided by contracting companies (Dubbert *et al.* 2021). In the cases of Tunisian olive oil companies, the commitment to implementing environmentally friendly actions (rationalization of water consumption, reduction of pesticides and insecticides) remains largely compliance-based, with minimal financial or technical support from dominant firms, limiting the extent of environmental improvements (Achabou *et al.* 2017). This may reflect that the market has not yet shifted significantly toward a demand for 'green products,' reducing the incentive for industries to adopt sustainable practices. Alternatively, it could suggest that industries underestimate the growing consumer interest in sustainability. Either way, the misalignment between market trends and industry actions presents a significant barrier to the broader adoption of sustainable practices. Agricultural advisory services linked to agribusinesses can raise concerns about conflicts of interest. For example, in China, advisors connected to agribusinesses recommend pesticides 18% more often than independent advisors (Wan *et al.* 2019). Similarly, in Brazil, 40% of the support farmers receive comes from vendors of fertilizers and agrochemicals, raising questions about the objectivity of the advice provided. Additionally, lobbying by farming organizations that prioritize their own benefits over sustainability has been identified as another barrier to promoting sustainable practices (Latawiec *et al.* 2017).

Governments can influence the change in farming practices through policy (David *et al.* 2022). Government subsidies are a strong motivator of SPPAs, especially regarding sustainable pesticide application behavior (Li *et al.* 2023; Xiang & Gao 2023). While subsidies effectively promote SPPA adoption, penalties also drive sustainable practices. Penalties, when strictly enforced, deter harmful activities and encourage compliance by increasing the economic costs of unsustainable behaviors (Zhou & Han 2024). They also motivate farmers to adopt environmentally friendly practices, such as straw return, by creating disincentives for non-compliance and reinforcing community norms (He *et al.* 2023). With subsidies and education, penalties form a comprehensive policy framework to ensure widespread SPPA adoption. Other policies and incentives such as training, public awareness campaigns, field demonstrations and workshops can help to encourage SPPA adoption by educating and changing farmers' perception of their ability to perform a practice (Phung & Dao 2024). On the other hand, institutional failures such as corruption, non-transparent governance structures, or unclear governance structures act as a barrier (Martin *et al.* 2015; David *et al.* 2022). However, this has mostly been reported in low- and middle-income countries.

Farmer-specialized cooperatives are an important player in the interactions between farmers and the government. The interactions between the government, farmer cooperatives, and individual farmers will influence the simulated progression of decision making among the three parties (Teng *et al.* 2022). The government's regulatory measures and incentives (like rewards and penalties) encourage cooperatives to manage farmers' production practices effectively. Cooperatives play a crucial role by supervising farmers, offering training, and providing financial incentives to adopt SPPAs (Teng *et al.* 2022). A notable case from the Wufeng District Farmers' Association in Taichung, Taiwan, shows how contractual price guarantees, input provision, collective pest management, and corporate sponsorship expanded environmentally friendly contract farming to nearly 58 hectares in five years (Yen & Chen 2021). Thus, cooperatives are vital in promoting SPPA adoption and linking policy to farmer behavior.

Extension services provided by experts played a key role in raising awareness about the negative effects of pesticides and providing the technical knowledge needed to implement sustainable pest management strategies (Wuepper *et al.* 2021). Farmers with frequent contact with extension agents were significantly more likely to adopt biological control methods in Iran (Abdollahzadeh *et al.* 2015). However, many farmers increasingly rely on peer networks and social media rather than traditional agricultural experts for advice on sustainable soil management. Farmers, particularly in the UK and Hungary, expressed greater trust in other farmers, valuing practical, firsthand knowledge over academic or governmental expertise. This shift is driven by a perception that experts often lack a deep understanding of the farmers' real-world challenges. The growing use of farmer-to-farmer interactions and social media highlights a significant change in how agricultural decisions are made, with peer networks becoming a more influential source of information (Rust *et al.* 2022). For example, In Taiwan, nearly 70% of strawberry farmers regularly exchange information with peers, discussing pest and disease outbreaks, control strategies, and pesticide use across all age groups (Huang *et al.* 2022). However, the ease of sharing on social media also facilitates the spread of misinformation, undermining trust and delaying science-based practices. Strengthening information literacy and fact-checking mechanisms is essential to mitigate these risks (Chowdhury *et al.* 2023).

These observations align with the findings that farmers' adoption of practice changes can be significantly influenced by peers, as individuals often align their behavior with perceived social norms (Michel-Guillou & Moser 2006). For instance, a case study in Cambodia concluded that decisions to increase the use of non-crop habitats for natural enemies are more influenced by the farmer's social environment (Bell *et al.* 2016). Similarly, French wine growers that participate in management schemes were driven by the perceived involvement of their peers (Kuhfuss *et al.* 2016). Moreover, studies on UK farmers, underscore the significant impact of peers on the adoption of SPPAs (Mills *et al.* 2017; Oerlemans & Assouline 2004).

Additionally, non-governmental organizations (NGOs) also play a variety of roles in advancing the adoption of SPPAs, including bridging information gaps, participating in public decision-making, accessing markets, and shaping legislative frameworks. A case study of small-scale farms in Nicaragua suggests that the efficacy of NGOs in facilitating the adoption of SPPAs may be enhanced if NGOs employ a non-centrist approach, which means a more bottom-up, two-directional relationship, collaborating closely with local stakeholders, engage in mutual learning and teaching as they collectively advance toward solutions for their social challenges (Dyck & Silvestre 2019). A case study in Taiwan highlights an NGO's use of the participatory guarantee system (PGS)- a community-based, locally driven alternative to third-party certification- to promote environmentally friendly farming. By involving producers, consumers, and other stakeholders in joint farm visits and decision-making, PGS fosters trust, transparency, and shared learning. Over six years, this approach expanded eco-friendly farming from 3.3 to 284 hectares, demonstrating its potential to advance the adoption of SPPAs (Chen *et al.* 2018; Lo 2024).

There are notable differences in how relationships between public and private sectors and farmers influence the adoption of SPPAs, often leading to contrasting outcomes. In Switzerland, farmers receiving advice from private companies are 9–10% more likely to rely on synthetic pesticides for pest management compared to those advised by public extension services (Wuepper *et al.* 2021). In contrast, farmers advised by public extension workers are more likely to adopt preventative pest control measures. Furthermore, when farmers receive advice from multiple public extension services (e.g., different organizations), the likelihood of adopting preventative measures increases (Wuepper *et al.* 2021). In China, the adoption of sustainable agrochemicals, such as those used by coffee farmers in Yunnan and orange farmers in Hubei, is shaped by interactions between public and private sector advisory services. However, the primary leadership often depends on the context: For instance, in Yunnan, agribusinesses like Nestlé play a leading role by providing inputs, training, and certification standards, while in Hubei, local government initiatives promote organic fertilizers to address environmental goals. This highlights the need for coordination between sectors to optimize adoption and sustainability outcomes (Rogers *et al.* 2023).

CHALLENGES TO PROMOTING SPPAS

The adoption of sustainable farming practices is often hindered by several key challenges. High costs, lack of financial support, ineffective information dissemination, weak institutional frameworks, and limited stakeholder collaboration are among the key hurdles for adopting SPPAs. Addressing these challenges is essential to promoting sustainable farming on a global scale (David *et al.* 2022).

Farmers are often slow to shift to adopt SPPAs due to concerns about the costs involved, pest pressure, and the lack of effectiveness of SPPAs. Farmers often face economic pressures and prioritize profitability, making them more likely to rely on chemical controls rather than adopting SPPAs, such as biological control. Therefore, despite efforts like IPM and associated subsidies, there has been little reduction in overall pesticide use in California (Epstein & Bassein 2003). The perceived lack of effectiveness of SPPAs is closely linked to gaps in ecological knowledge. The comparative effectiveness of SPPAs versus conventional pest control methods is a critical criterion for many farmers (Sharifzadeh *et al.* 2018). A significant component of SPPAs involves the use of biological control agents (i.e., natural enemies of insect pests) to reduce pest populations. However, knowledge about biological control is often limited among some farmers. For example, Honduran farmers who predominantly rely on synthetic pesticides tend to have low awareness of biological control, particularly regarding its potential effectiveness and proper implementation (Wyckhuys & Neil 2007). Kiwi farmers in China can perceive SPPAs as high-risk method and therefore choose not to adopt these measures (Xiang & Gao 2023).

Institutional failures further exacerbate these challenges by creating an unstable environment that discourages investment in SPPAs. Weak governance frameworks, corruption, and lack of regulatory enforcement undermine farmers' trust and willingness to engage in sustainable practices (Martin *et al.* 2015). In Malaysia's palm oil sector, for instance, smallholders face ambiguous land rights, making long-term investment in sustainable practices risky. Cases of land-grabbing and corruption often discourage farmers from adopting innovative approaches (Martin *et al.* 2015). Institutional voids also hinder access to resources such as technical knowledge, financial support, and market opportunities. Farmers operating in marginal regions often remain disconnected from global supply chains, limiting their awareness of sustainable practices and technologies. For example, Sabahan palm oil smallholders are reluctant to adopt sustainable practices due to poor infrastructure, lack of education, and weak institutional support systems (Martin *et al.* 2015). Additionally, there is a lack of proper extension infrastructure that effectively disseminates SPPAs knowledge to farmers. For example, in certain regions, lack of extension services leads to pesticide misuse which increases health risks and hinders the adoption of SPPAs (Ngowi *et al.* 2007). However, sometimes changing the mindset is not enough. In some cases, farmers are willing to adopt SPPAs, but their actual behavior might not match their willingness (Qiao *et al.* 2022). Factors such as education, social network, and age can have a major impact on the gap between farmers' expressed willingness to adopt SPPAs and their actual behavior (Qiao *et al.* 2022). This discrepancy may partly arise from social desirability bias, where individuals express socially acceptable intentions (e.g., willingness to adopt sustainable practices) that do not translate into action due to other underlying barriers, such as economic constraints or limited access to resources (Grimm 2010). Additionally, overcoming deeply ingrained traditional habits poses another challenge. In some regions, long-standing practices significantly contribute to unsustainable farming behaviors (Pirmoradi & Rostami 2021).

Establishing regulations for sustainable agricultural practices is an important strategy to promote the adoption of SPPAs. However, such regulations can sometimes inadvertently marginalize smallholder farmers and accelerate land transfers to larger-scale operations (Rogers *et al.* 2023). Additionally, the higher costs associated with implementing SPPAs present a significant barrier to their adoption, particularly for resource-limited farmers (Sharifzadeh *et al.* 2018; Li *et al.* 2023). Another example is the Food Quality Protection Act (FQPA) in California which successfully reduced the use of hazardous pesticides. However, this reduction primarily resulted in the substitution of older chemicals with newer ones, rather than promoting the adoption of SPPAs. The shift to alternative pesticides has not substantially advanced the use of non-chemical methods, and IPM programs have been effective only when they provide direct economic benefits to growers. Without such incentives, the adoption of SPPAs remains limited, emphasizing the need for more targeted and robust strategies to encourage sustainable practices (Epstein & Zhang 2018). Additionally, strict food safety standards designed to prevent contamination and ensure consumer safety can inadvertently discourage practices that promote ecological sustainability. For instance, these standards often require farmers to remove non-crop vegetation and wildlife habitats, practices that align with food safety but contradict biodiversity conservation efforts (Baur 2022). Similarly, concerns about microbial contamination may lead farmers to abandon organic soil amendments like compost in favor of synthetic fertilizers, which do not enhance ecosystem services such as pest predation (Baur 2022). This regulatory emphasis on immediate food safety often takes precedence over long-term environmental goals, creating a significant barrier to the adoption of SPPAs. SPPAs, such as habitat conservation and integrated pest management, which are central to sustainability, rely on voluntary incentives and fragmented policies that lack the enforcement mechanisms and consistency of food safety regulations. Furthermore, market-driven pressures to comply with strict food safety standards reinforce this prioritization, leaving farmers with limited flexibility to implement sustainability-focused practices (Baur 2022).

Systems or policies designed to promote the adoption of SPPAs do not always achieve their intended outcomes. For instance, while the division of labor is often predicted to enhance efficiency, and outsourcing services theoretically could improve resource utilization and facilitate SPPA adoption, the reality can differ. In China, pesticide outsourcing services provided by organizations or professional cooperatives, originally intended to promote sustainable practices by reducing synthetic pesticide use, have instead led to increased herbicide application and reduced manual weeding (Yang *et al.* 2023). The authors attribute this outcome to imperfections in the outsourcing service market, which shift farmers' practices from labor-intensive processes to capital-intensive ones, such as increased reliance on synthetic pesticides (Yang *et al.* 2023).

In addition to the public sector, the private sector plays a crucial role in promoting the adoption of SPPAs. Large companies can sometimes encourage sustainable practices; however, relying solely on them is not always an effective solution. Market forces, specifically participation in global value chains (GVCs), influence the adoption of SPPAs. GVCs involve production processes distributed across multiple countries, with firms in the Global South supplying components or raw materials while multinational corporations set production standards. For example, Tunisian olive oil companies have adopted SPPAs, such as reducing pesticide use, to comply with international market standards, particularly among export-oriented firms (Achabou *et al.* 2017). While compliance with organic certification has driven product upgrading, broader environmental challenges persist. One significant issue is the management of vegetable water, a byproduct of olive oil production. Improper disposal of vegetable water, which contains high pH levels, fatty substances, and oxygen-consuming organic content, can harm aquatic ecosystems. The volume of vegetable water generated depends on the processing method used. Modern techniques, such as two-phase centrifugation, significantly reduce waste compared to traditional methods. However, in countries like Tunisia, adopting these technologies is hindered by limited financial and technical resources. This example illustrates that while market demands can drive targeted improvements, such as pesticide reduction, addressing broader environmental challenges like pollution management requires more robust financial and technical support systems. The absence of collaborative assistance from dominant GVC actors limits the potential for comprehensive environmental upgrading (Achabou *et al.* 2017). Similarly, contract farming practices can also affect the adoption of SPPAs. Contract farmers in Ghana, particularly those engaged in agreements emphasizing productivity and input provision, rely more heavily on chemical inputs, leading to less sustainable practices compared to non-contract farmers. Contracts focusing on short-term yields often discourage the adoption of SPPAs, demonstrating the need for contract structures that align productivity goals with sustainable practices (Dubbert *et al.* 2021).

Most of these challenges have been identified through past research on farmers' behavior, primarily using correlation studies. However, studies that focus solely on correlations between factors and behavioral changes have been deemed insufficient for predicting the effectiveness of intervention measures designed to modify behavior (Albarracín *et al.* 2024). This limitation arises from findings that the most effective factors for driving behavioral changes differ significantly between correlation-based studies and experimental intervention studies (Albarracín *et al.* 2024). For example, for the off-farm factors that are linked to behavior changes, correlation studies generally identified trustworthiness as the most important factor leading to behavior change while actually intervention studies have identified access to be the most important factor (Albarracín *et al.* 2024). Access refers to the ease with which the environment enables a given behavior to occur. For example, lowering the price of environmentally friendly pesticides would increase access to these SPPAs. These findings underscore the importance of prioritizing data from intervention studies to identify effective strategies for encouraging farmers to adopt SPPAs. Future research should focus on intervention-based approaches rather than solely on correlation studies exploring the links between factors and behaviors. Additionally, the influence of various factors on the adoption of SPPAs can change over time due to the dynamic nature of social, political, and economic environments (Li *et al.* 2023). This highlights the critical need for long-term studies to monitor and understand the factors driving farmers' behavior.

Oversimplifying farmers' motivations is likely a significant limitation in promoting the adoption of SPPAs. While financial incentives are undoubtedly critical, prioritizing immediate livelihood needs often poses a substantial hurdle to the adoption of SPPAs. Farmers facing economic precarity, particularly in the Global South, may focus on short-term productivity and income over long-term sustainability, even when financial incentives are available. While this reality highlights the potential of increasing financial incentives to encourage the adoption of SPPAs, the issue is far more complex. For instance, oversimplifying farmers' motivations has been suggested to be a significant issue that has hindered the environmental effectiveness of the European Union's Common Agricultural Policy (CAP), including the adoption of SPPAs. Despite substantial financial investments, the CAP has fallen short of achieving its biodiversity goals. Biodiversity is intrinsically linked to SPPAs, as practices like reduced pesticide use, integrated pest management, and biological control help preserve ecosystems by minimizing harm to non-target species, supporting natural pest control, and fostering pollinator populations. This failure stems from an overemphasis on economic incentives while neglecting the social and contextual factors that influence farmers' decisions. For instance, studies have shown that financial payments, when not paired with social and technical support, fail to overcome barriers such as limited resources, lack of trust, and contextual constraints (Brown *et al.* 2021).

SOLUTIONS FOR PROMOTING SPPAS

To encourage the broader adoption of SPPAs, addressing concerns about the potential costs and risks is essential. Policy measures such as financial incentives and education programs can play a crucial role in encouraging broader adoption of sustainable farming practices. One effective strategy to reduce the concerns and psychological barriers associated with SPPA adoptions is the establishment of crop insurance systems. Research has shown that crop insurance can reduce synthetic pesticide use by up to 33% (Li *et al.* 2022), demonstrating its potential to promote sustainable practices. For risk-averse farmers, targeted policies should prioritize reducing financial uncertainties. For instance, initiatives like insurance schemes tailored to SPPA adoption, financial incentives, or income-stabilizing subsidies all serve to stabilize farmers' incomes, thereby reducing the perceived risks associated with adopting SPPAs (Guo *et al.* 2021). For example, farmers who adopt SPPAs could qualify for lower insurance premiums or receive higher indemnities. Specific measures could include offering reduced insurance premiums or higher indemnities to farmers who adopt SPPAs, providing a tangible economic benefit that offsets the potential costs. By alleviating financial concerns, these approaches might facilitate the transition to sustainable farming practices while addressing farmers' apprehensions about economic stability. However, insurance does not always promote the adoption of SPPAs, as research indicates that crop insurance may sometimes have unintended consequences, such as increased pesticide use. Studies have shown that insurance can incentivize farmers to adopt more pesticide-intensive farming practices, particularly by encouraging the cultivation of high-risk, high-input crops and increasing pesticide use per hectare (Möhring *et al.* 2020). This occurs because the financial safety net provided by insurance reduces the economic risks of crop failure, making farmers more likely to invest in intensive agricultural practices. To ensure that insurance aligns with the goals of SPPAs, policy frameworks should incorporate conditions or incentives that explicitly encourage sustainable practices. For instance, insurance schemes could be linked to IPM or organic certification, offering reduced premiums or additional coverage for farmers who minimize synthetic pesticide use. Similarly, combining insurance programs with education and technical support for SPPAs can help farmers adopt risk-reducing sustainable practices without compromising productivity or profitability. By addressing these complexities, insurance policies can be designed to both mitigate risks and promote environmentally sustainable farming systems.

To improve farmers' risk tolerance- whether by influencing risk attitudes or building resilience- strategies should emphasize enhancing educational programs, engaging key stakeholders, fostering networking opportunities, promoting cluster-based approaches, and utilizing technology. These efforts can help shift perceptions, build confidence, and empower farmers to better manage risks in their operations (Agussabti *et al.* 2020). Additionally, the perceived lack of effectiveness in SPPAs is often due to a lack of knowledge and confidence in their implementation. To address this, it is crucial to expand training programs that equip farmers with the necessary knowledge and skills. This is especially important because behavioral skill training has been identified as a moderately effective approach for driving behavior change (Albarracín *et al.* 2024).

A recurring theme in the literature is the role of literacy and education as both a factor influencing the adoption of SPPAs and a challenge limiting their adoption. The transfer of knowledge from researchers or government agencies to farmers relies heavily on extension workers. Therefore, establishing effective extension systems is essential to educate farmers about different types of SPPAs. For example, in Honduras, farmers with greater knowledge of biological control were more likely to adopt environmentally friendly pest control approaches (Wyckhuys & Neil 2007). Local meetings, training, and public awareness campaigns are also important activities that enhance knowledge and motivation among farmers to promote sustainable practices (Ataei *et al.* 2021). Interestingly, in some regions, the longevity and expertise of a service provider have been identified as more important for building trust than whether the advisory service is public, private, or charitable (Sutherland *et al.* 2013). Consistent funding for well-established agencies or their affiliates is, therefore, more effective in influencing farmer behavior in the short term compared to short-term "contract" advisory projects involving inexperienced service providers (Sutherland *et al.* 2013).

In addition to knowledge dissemination by extension workers, farmer-to-farmer interactions are increasingly recognized as playing a crucial role in spreading knowledge (Rogers *et al.* 2023). In Taiwan, 70% of farmers seek advice from fellow farmers, 60% consult agricultural supply stores, 30% turn to research and extension stations, and fewer than 10% rely on farmers' associations (Huang *et al.* 2022).

Social media, for instance, has become a common channel for information sharing between farmers (Rogers *et al.* 2023). While not directly related to pest control, studies on water-saving behaviors offer insights that could inform strategies for promoting SPPAs. For example, a study in France found that social comparison nudges- such as sharing individual water use records with a community of farmers- reduced excessive irrigation among those using the most water and increased irrigation among those who did not irrigate at all. This intervention, facilitated by smart irrigation meters, proved to be a low-cost and effective method to change farmers' behaviors (Chabé-Ferret *et al.* 2019). Such social comparison nudges, along with farmer-to-farmer interactions, should be incorporated into the design of extension systems to facilitate the adoption of SPPAs better.

As discussed in previous sections, certain policies aimed at promoting SPPAs have, at times, led to undesirable outcomes. To avoid repeating these mistakes, it is essential to leverage current knowledge and design evidence-based strategies. Recent studies have identified that one of the most significant factors driving behavioral change is access to resources that facilitate the adoption of specific practices. Access encompasses the availability, affordability, and logistical ease of utilizing resources, such as providing necessary tools, reducing financial barriers, and ensuring convenient infrastructure. By removing environmental constraints, access creates tangible opportunities for individuals to act on their intentions and adopt desired behaviors effectively (Albarracín *et al.* 2024). For environmentally friendly behaviors, increasing access has the greatest impact on behavior change, followed by enhancing social support and improving behavioral skills. A promising example of an initiative that could address these factors is Taiwan's "Plant Doctor" system (McGovern & To-Anun 2016). This system equips farmers with essential technical knowledge and skills they may lack, increasing their capacity to adopt sustainable practices. By outsourcing SPPA-related services to organizations or extension workers like plant doctors, accessibility can be improved while also providing third-party certification for health and environmental stewardship. When combined with financial support or subsidies from the government, such initiatives could further facilitate the adoption of SPPAs by ensuring farmers have both the resources and guidance they need. However, a 2019 survey shows limited engagement across age groups- only 29% of farmers aged 31–40 and 18% of those aged 41–50 consult plant doctors, with no participation among those over 50 (Huang *et al.* 2022). This suggests the system's impact is uneven and requires further evaluation. Future research should evaluate its potential to enhance accessibility and foster sustainable agricultural practices. In addition to access, other factors, such as beliefs, behavioral attitudes, knowledge, administrative sanctions, and material incentives, appear to have a comparatively limited effect (Albarracín *et al.* 2024). The higher cost of SPPAs is a strong inhibitor of the adoption of these more environmentally sustainable plant protection approaches (Sharifzadeh *et al.* 2018; Li *et al.* 2023). Therefore, increasing subsidies for green pesticides and identifying additional strategies to boost farmer household incomes will be essential ways to improve accessibility and enhance the use of SPPAs (Li *et al.* 2023).

In addition, adopting SPPAs can be viewed as a health-promoting behavior for farmers. It is, therefore, important to approach these behaviors from a health perspective. Research suggests that the key factors influencing health-related behavioral changes include access, habits, material incentives, and descriptive norms (Albarracín *et al.* 2024). This indicates that when designing strategies to promote the adoption of SPPAs, it is important to understand whether farmers view SPPAs primarily as environmentally friendly practices or health-promoting behaviors. The framing of SPPAs can influence the most effective targets for behavior change.

Researchers and policymakers should avoid oversimplifying farmers' motivations and practices (Brown *et al.* 2021). Farmers possess valuable local knowledge and methods for protecting crops, and dismissing their knowledge or labeling them as ignorant does little to foster a better understanding of their behavior (Rogers *et al.* 2023). For instance, the European Union's CAP, which aims to promote sustainable practices, has faced challenges due to an oversimplified view of farmers' motivations. This has led to undesirable outcomes, as the policy relies heavily on economic incentives while neglecting the social and contextual factors that influence farmers' decisions. To improve its effectiveness, policies must consider the diverse and complex motivations that drive farmers to adopt environmentally sustainable practices. Farmers' adoption of sustainable crop protection practices is strongly influenced by behavioral factors, including time preferences and social influence. Farmers who heavily prioritize immediate rewards over future benefits are less likely to adopt practices that require upfront effort but provide long-term advantages (Albarracín *et al.* 2024). Social influence plays a crucial role in the adoption of sustainable practices, as farmers are more likely to adopt these methods when their peers do, but they may resist if their community is hesitant to change. This dynamic highlights a potential conflict between government policies that promote sustainable practices and the network effects within farming communities. While government policies may provide financial or technical incentives, the collective attitudes and behaviors of farming networks can either amplify or hinder their effectiveness. These behavioral factors, though often overlooked, are critical to ensuring that sustainable practices are widely and effectively adopted (Finger *et al.* 2024).

CONCLUSION AND FUTURE DIRECTIONS

The current agricultural system is heavily influenced by a Western industrialized perspective, prioritizing productivity over sustainability, often at great environmental cost (Ilbery & Bowler 2014). Conventional, intensive plant protection practices are particularly widely documented as key contributors to agriculture's negative impact on sustainability (Matthews 2018). To address this, it is essential to reform agricultural practices, particularly pest and pathogen management, by promoting the adoption of SPPAs as a crucial step toward a sustainable system.

However, changing farmers' behavior remains challenging, as crop production is both a livelihood and a primary source of income, with productivity and crop quality directly tied to financial stability. This focus on productivity often comes at the expense of sustainability. Researchers and governments must lead in promoting SPPAs by identifying and addressing the key factors influencing behavioral change, ultimately encouraging widespread adoption of sustainable practices.

We have identified various farm-related and non-farm factors that influence the adoption of SPPAs (Fig. 1). Farm-related factors include concerns about health risks associated with traditional plant protection methods (e.g., synthetic pesticides), risks related to productivity and costs, farmers' attitudes toward these risks, their knowledge or literacy about SPPAs, perceived behavioral control, personality traits, trust levels, and farm typologies. Non-farm factors encompass social capital, interactions with stakeholders, government financial support and subsidies, and market and consumer dynamics. Among these, interactions with different stakeholders in the agricultural system play a crucial role. For example, buyers significantly influence SPPA adoption, particularly when they impose regulations requiring specific plant protection practices, effectively compelling farmers to adopt SPPAs. Understanding the flow of capital, materials, and power within the agrochemical industry is crucial for uncovering how agribusinesses influence the adoption of SPPAs (Rogers *et al.* 2023). Equally important is preventing the marginalization of smallholders in decision-making processes dominated by large-scale agrochemical agendas, as many small-holders lack access to alternative pest control technologies (Rogers *et al.* 2023).

Governments and farm cooperatives also play a significant role in shaping SPPA adoption- sometimes encouraging it, but at other times inadvertently hindering it. It is essential to examine the network of government policies related to food safety, sustainability, and pollution control to understand how these interconnected policies impact the use of SPPAs (Rogers *et al.* 2023). For instance, food safety standards often conflict with sustainability by requiring habitat removal and discouraging organic amendments, which harms biodiversity (Baur 2022). Similarly, regulations like California's FQPA reduced hazardous pesticides but favored chemical substitutions over non-chemical methods, limiting SPPA adoption (Epstein & Zhang 2018). Addressing these challenges requires systemic reforms that align sustainability and food safety goals. Such reforms must be supported by coherent policies and incentives that empower farmers to adopt sustainable plant protection strategies (Baur 2022).

Farmer-to-farmer interaction is a key factor influencing the adoption of SPPAs, as demonstrated in various cases. Additionally, NGOs can play a significant role in promoting sustainable practices. For instance, in Nicaragua, an NGO successfully encouraged the adoption of conservation agriculture among small-scale farmers by using a bottom-up approach. This method prioritized local experimentation, two-way knowledge exchange, and farmer-led innovation, focusing on collaboration and capacity building rather than rigid, top-down standards. This approach proved highly effective, showcasing the potential for sustainable and lasting change (Dyck & Silvestre 2019).

However, these same factors can sometimes pose challenges to SPPA adoption. Farmers' traditions can be resistant to change due to farm-related characteristics such as risk tolerance, perceptions, and knowledge gaps. Additionally, the absence of effective extension systems and knowledge dissemination pathways often hinder SPPA adoption. The complexity of factors influencing farmers' behavior means that well-intentioned policies and regulations can sometimes have unintended negative consequences, reducing SPPA adoption rates.

The private sector, such as buyers, can be both a driving force and a barrier to SPPA adoption. Similarly, researchers and governments occasionally oversimplify farmers' behavior, leading to undesirable outcomes. This is likely a widespread issue stemming from limited research on the topic, communication gaps, and potential biases among researchers and extension workers.

Based on current knowledge, several solutions have been proposed. Policies or strategies that reduce risk, enhance farmers' literacy and education, and improve the accessibility of SPPAs are widely recognized as critical for promoting adoption. An emerging theme is the importance of farmer-to-farmer communication in achieving education and disseminating information effectively. These collaborative efforts, combined with targeted policies, can greatly enhance the adoption of sustainable practices.

The lack of extension services significantly hinders the adoption of SPPAs. To promote safer and more sustainable practices, improved education and policy reforms are essential (Ngowi *et al.* 2007). Researchers and policymakers must also recognize the complexity of the issue, avoiding oversimplification or quick labeling of farmers' intentions and behaviors. A more nuanced approach, involving enhanced access to training, education, and inclusion in policy development, along with a communication framework rooted in social networks rather than solely governmental channels, can address the shortcomings of existing policies (Brown *et al.* 2021).

As recent studies highlight, improving accessibility is a key factor in facilitating behavior change toward environmentally sustainable practices (Albarracín *et al.* 2024). Creating systems that enhance the accessibility of SPPAs is crucial. Beyond financial support measures such as government subsidies, one promising solution is outsourcing SPPA-related services to extension workers, including plant doctors. This approach could reduce knowledge barriers, make SPPAs more accessible, build trust between professionals and farmers, and simultaneously create career opportunities in plant protection disciplines.

While considerable knowledge has been accumulated on factors influencing farmers' behavior and adopting SPPAs, significant gaps remain, particularly in regional studies.

Take Taiwan, for example. The government has implemented various policies to promote the adoption of SPPAs and reduce associated risks and economic burdens. The Ministry of Agriculture (MOA) and its affiliated Animal and Plant Health Inspection Agency (APHIA) have introduced several initiatives to support farmers. Since 2011, the MOA has established the "Farmers' Academy," creating a comprehensive agricultural training system to enhance farmers' knowledge and technical capacity. In 2015, the government introduced crop disaster insurance to mitigate financial risks for farmers affected by natural disasters. Additionally, the "Ten-Year Action Plan for Halving Chemical Pesticide Risks" was launched to reduce reliance on chemical pesticides and promote SPPAs. APHIA has also played an active role in encouraging sustainable practices. The agency organizes the IPM Award, recognizing individuals across the agricultural supply chain who have made outstanding contributions to IPM. Furthermore, financial incentives, such as subsidies for environmentally friendly plant protection materials- including subsidies for natural enemies used in biological control- have been implemented to facilitate the SPPAs' adoption. Despite these policies, their effectiveness remains largely unevaluated. Limited empirical evidence exists on their impact on farmers' decision-making, economic viability, and pesticide reduction, necessitating further investigation to refine and optimize policy interventions.

Agricultural systems are diverse and shaped not only by environmental factors but also by local cultures. Conducting region-specific studies is essential to account for the heterogeneity in agro-climatic and agronomic conditions that influence SPPA adoption. Such research can identify region-specific opportunities and challenges, enabling the design of tailored policies that make SPPA adoption more feasible in certain areas while addressing barriers in others. This localized approach will not only enhance SPPA promotion at regional levels but also contribute to more effective global adoption strategies. Another major gap lies in incorporating psychological perspectives into studies of farmers' behavior. Recent research has demonstrated the value of psychology in understanding factors that drive behavior change (Albarracín *et al.* 2024). Future work on SPPA adoption should integrate psychological frameworks and consider cultural and regional contexts. This approach will lead to a deeper understanding of farmer behavior and more effective strategies for promoting SPPAs.

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農民採用永續植物保護措施的誘因

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摘要

林柏安、廖婉頤、何率慈、謝佳維、李宗翰。2025。農民採用永續植物保護措施的誘因。台灣農業研究 74(2):87–112。

永續植物保護措施 (sustainable plant protection approaches; SPPAs) 在減輕有害生物防治所引發的環境衝擊與促進永續農業系統的建立方面，具有關鍵重要性。本專題論述統整影響農民採用 SPPAs 的多重因素，並著重於不同層級因素與其交互作用。與農戶相關 (farm-related) 的因素包括健康風險、風險認知、經濟能力以及對 SPPAs 成效與實施方式的理解；而非農戶層面的因素 (non-farm-related) 則涵蓋社會規範、政府政策以及與利害關係人的互動，這些因素同樣影響 SPPAs 的採用行為。現有研究顯示，社會網絡 (如農民間的互動) 與推廣服務，在知識傳遞與 SPPAs 採用過程中扮演關鍵機制。儘管 SPPAs 在環境與經濟層面有顯著益處，但高成本、成效認知不足以及有限的資訊與技術資源，仍為農民採用 SPPAs 的主要障礙。政府介入，如提供補助、培訓計畫及作物保險，為降低 SPPAs 相關風險與經濟負擔的重要工具。但政策碎片化與市場壓力的矛盾，往往對 SPPAs 的推廣形成阻礙。總結過去研究，若要提升 SPPAs 之採用，建立整合且基於實證的政策，協調各方利害關係人的激勵機制，並運用行為科學與心理學促進農民採用 SPPAs，同時考量區域文化差異為相當重要的工作。然而，目前相關研究相對匱乏。推動 SPPAs 的廣泛應用，仰賴長期研究與研究人員、政策制定者及農業組織的協同合作，以構建具韌性且永續的植物保護策略與農業生產體系。

關鍵詞：農民行為、整合性有害生物管理 (IPM)、農業永續、農業政策、利害關係人。

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